

New Energy-saving Technologies in the Evaporation Section of Alumina Production

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Abstract

Under the background of the global "Dual Carbon" strategy, the alumina industry needs to reduce energy consumption in its evaporation process urgently. Based on engineering practices at Henan Jiuye Chemical Equipment Co., Ltd., this paper provides an introduction to such energy-saving technologies as seven-effect sectionalized evaporators (Patent No.: ZL201220432718.4) and evaporative condensers (Patent No.: ZL201821142093.1). The seven-effect evaporator uses such patented designs as sectionalized structures, innovative film distributors, vortex demisters, etc. to address such issues as uneven liquid films and low demisting efficiency in conventional equipment, achieving over 10 % improvement in evaporation efficiency. The evaporative condenser integrates flash steam condensation with circulating water cooling, significantly reducing equipment footprint and energy consumption, and it has brought annual cost savings of 11.22 million RMB (1.57 MUSD/y approx.) in the Guangxi Huasheng project. The eight-effect evaporator solution proposed for low-concentration spent liquor can further reduce steam consumption through optimized heat balance and temperature distribution, saving over 27 million RMB annually (3.77 MUSD/y approx.). The research results in this paper can provide technical references for the green transformation of the alumina industry.

Keywords: Alumina, Evaporation, Seven/Eight-effect evaporator, Evaporative condenser, Energy saving and consumption reduction.

1. Company Profile

Founded in 1999, Henan Jiuye Chemical Equipment Co., Ltd. is an integrated high-tech enterprise that focuses on scientific research, design, fabrication, installation and service, and is a "National Specialized, Sophisticated, Distinctive and Innovative Little Giant Firm" in Henan Province.

The company specializes in the design, manufacturing, and installation of pressure vessels, various evaporators, chemical storage tanks, towers, and bio-fermentation equipment. Its flagship products – evaporators and crystallization equipment – are widely used in such industries as alumina production, hydrometallurgy, papermaking, wastewater treatment, bio-fermentation, food processing, chemical engineering, pharmaceuticals, salt production, etc. The company's energy-saving seven-effect two-stage falling-film evaporator technology is in the leading position around the world, earning the company the Second Prize for Technological Progress from the China Nonferrous Metals Industry Association in 2013. The company holds over 37 patents on technologies for evaporators and other equipment [1–3].

Throughout its development journey, the company has successfully sold its products to such alumina refineries as Weiqiao Aluminum & Power, Xinfu Group, Chinalco Group, Jinjiang Group, Rusal Group, Guanglv Group, Jisco Group, Tianguai Aluminum, Guizhou Qiya, Lubei Chemical

Group, and Zhongchao Aluminum, earning excellent reputation. Meanwhile, its products have been successfully exported to overseas markets, including Rusal's Kenya Project, Jisco's Jamaica Project, Jinjiang's Indonesia Project, Chinalco's Indonesia Project, etc., gaining extensive market presence and good social reputation. In 2022, the company designed a seven-effect 580 t/h evaporator for Guangxi Tiandong Jinxin Chemical Co., Ltd.'s alumina production project, which became the world's largest seven-effect tubular falling-film evaporator in the alumina industry and was awarded the "Outstanding Contractor" award. In the same year, the sodium aluminate solution evaporation system of Chinalco Guangxi Huasheng New Materials Co., Ltd.'s 2 Mt/y alumina project contracted by the company was rated as a "Quality Project" in the non-ferrous metal industry for 2020–2021, fully demonstrating the company's outstanding capabilities in design, construction, and installation.

2. Advent and Practice of New Seven-effect Sectionalized Evaporator Technology and Equipment

The company independently developed seven-effect evaporator (Patent No. ZL201220432718.4) uses a unique design and innovative manufacturing process to achieve more efficient energy utilization during evaporation [1]. The multi-effect evaporation principle allows for full recovery and utilization of latent heat from steam, significantly reducing steam consumption. In 2013, this technology passed the scientific evaluation by the China Nonferrous Metals Industry Association, with attending academicians and experts unanimously judging that the equipment reached international leading levels and recommending accelerated promotion. Shandong Xinfu Group became the first to use this patented technology by retrofitting three sets of six-effect evaporators into seven-effect evaporators, achieving remarkable energy savings.

2.1 Applications of New Seven-effect Evaporator Technology and Equipment in Alumina Industry at home and Abroad (Including Eight-effect Evaporator)

- (1) Weiqiao Group's 2 sets of newly constructed 280 t/h seven-effect falling-film evaporators for low-concentration applications at Binzhou Beihai Huihong New Materials Co., Ltd. in 2015.
- (2) Shanxi Xinfu Chemical Co., Ltd.'s 1 set of newly constructed 300 t/h seven-effect falling-film evaporators for high-concentration applications in 2015.
- (3) Shandong Xinfu Group's 1 set of 400 t/h seven-effect split evaporators for high-concentration applications in 2015.
- (4) Yunnan Wenshan Aluminum's 1 set of 300 t/h seven-effect falling-film evaporators for high-concentration applications in 2017.
- (5) Guizhou Guang Aluminum's 1 set of 360 t/h six-effect falling-film evaporators for high-concentration applications in 2017.
- (6) Jingxi Tianguai Aluminum's 1 set of 370 t/h evaporators for high-concentration applications in its Phase I 2500 kt/a alumina refinery project in 2017.
- (7) Jisco's 2 sets of 300 t/h seven-effect falling-film evaporators for low-concentration applications at its Alpart alumina refinery in Jamaica in 2018.
- (8) Rusal's 1 set of 220 t/h seven-effect falling-film evaporators for low-concentration applications at its alumina refinery in Kenya in 2018.
- (9) Chinalco's 2 sets of 400 t/h evaporators for low-concentration applications at Guangxi Huasheng New Materials Co., Ltd. (Phase I) in 2019, which was awarded the "First Prize of Quality Engineering in China Nonferrous Metals Industry" after being put into operation.
- (10) Guangxi Longzhou Xinxiang Ecological Aluminum Industry Co., Ltd.'s 2 sets of 330 t/h seven-effect falling-film evaporators for high-concentration applications in 2020.
- (11) Jingxi Tianguai Aluminum's 1 set of 370 t/h evaporators for high-concentration applications in its Phase II 1700 kt/a alumina refinery project in 2020.
- (12) Guizhou Guang Aluminum's 1 set of 360 t/h seven-effect falling-film evaporators for high-concentration applications in 2020.

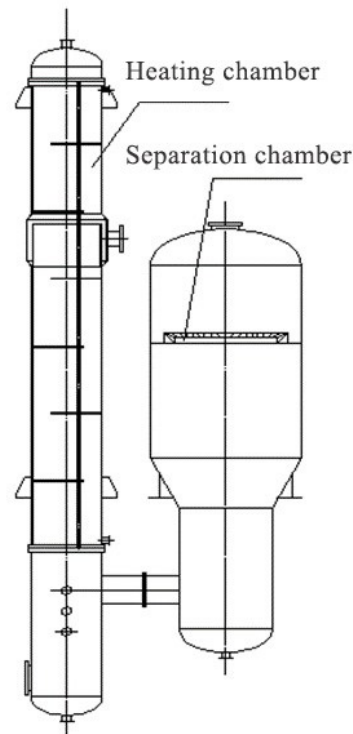
- (13) Shandong Lubei Chemical's 1 set of 440 t/h seven-effect falling-film evaporators for low-concentration applications in 2021.
- (14) Chinalco's 1 set of 500 t/h seven-effect falling-film evaporators for low-concentration applications at its alumina refinery in Indonesia in 2021.
- (15) Guizhou Qiya Phase III's 1 set of 360 t/h seven-effect falling-film evaporators for high-concentration applications in 2021.
- (16) Guangxi Tiandong Jinxin's 1 set of 580 t/h seven-effect falling-film evaporators for high-concentration applications in 2022, which was the world's largest evaporator unit at that time, awarded the Outstanding Construction Award.
- (17) Hebei Wenfeng Steel & Aluminum Phase I's 2 sets of 500 t/h seven-effect falling-film evaporators for low-concentration applications in 2023.
- (18) Jinjiang Group's 1 set of 400 t/h seven-effect falling-film evaporators for low-concentration applications at its Mempawah Phase I alumina refinery in Indonesia in 2023.
- (19) Guangxi Investment Lingang's 2 sets of 450 t/h seven-effect falling-film evaporators for low-concentration applications in 2023.
- (20) Chinalco's 2 sets of 500 t/h seven-effect falling-film evaporators for low-concentration applications at Guangxi Huasheng New Materials Co., Ltd. (Phase II) in 2023.
- (21) Guangxi Fangchenggang Zhongsilu's 2 sets of 500 t/h seven-effect falling-film evaporators for low-concentration applications in 2024.
- (22) Jingxi Tiangui Aluminum's 1 set of 370 t/h seven-effect falling-film evaporators for high-concentration applications in its Phase III alumina refinery project in 2024.
- (23) Chinalco's 1 set of 500 t/h seven-effect falling-film evaporators for high-concentration applications at its Henan branch in 2024.
- (24) Chinalco's 2 sets of 500 t/h seven-effect falling-film evaporators for medium-concentration applications at its Shandong branch (east line and south line) in 2024.
- (25) Chinalco's 1 set of 500 t/h seven-effect falling-film evaporators for high-concentration applications at its Zhongzhou branch in 2024.
- (26) Hebei Wenfeng Steel & Aluminum Phase II's 2 sets of 500 t/h seven-effect falling-film evaporators for low-concentration applications in 2025.
- (27) Luoyang Zhongchao New Materials Co., Ltd.'s 4 sets of 40 t/h MVR evaporator retrofitting project (adding non-standard equipment) in 2025.
- (28) Luoyang Xiangjiang Wanji Aluminum Co., Ltd.'s 1 set of six-effect evaporator station upgrade project in 2025.
- (29) Chinalco's 1 set of 550 t/h seven-effect evaporators for high-concentration applications at Guangxi Huayin Aluminum Co., Ltd. in 2025.
- (30) Shanghai Heavy Industry Industrial Investment Co., Ltd.'s 2 sets of eight-effect evaporators for low-concentration applications at East Hople's PT Westerfield Alumina Phase I 2 000 kt/a alumina refinery in Indonesia in 2025.

2.2 An Introduction to Seven-effect Evaporator Patented Technologies

The seven-effect two-stage split evaporator is an efficient evaporation device that operates on the principle of multi-effect evaporation. By repeatedly utilizing the latent heat of steam, it achieves high-efficiency concentration of solutions. In alumina production, this device is primarily used to evaporate and concentrate sodium aluminate solutions in order to the requirements of subsequent manufacturing processes [4].

The seven-effect evaporator unit uses split-structure design (as shown in Figure 1), which offers distinct advantages. It consists of seven evaporation effects, each containing a heating chamber, separation chamber, and collection chamber. The heating chamber serves as the core thermal source, housing a bundle of heating tubes through which steam flows. The heat transfers via the tube walls to the sodium aluminate solution outside, effectively heating and evaporating the solution. The separation chamber achieves efficient steam-concentrate separation during

evaporation. Located at the lower section of the heating chamber, the collection chamber collects the concentrates for subsequent transportation and processing.



Schematic Diagram of Split Evaporator

Figure 1. Schematic diagram of split structure of seven-effect evaporator.

The evaporation effects are interconnected through connecting pipes to form a complete evaporation system. The solution flows from the last evaporation effect to the upstream evaporation effects in sequence within the evaporator, while the steam moves from the upstream evaporation effect to the downstream evaporation effect. The counter-current flow takes full advantage of the latent heat of the steam, thereby enhancing evaporation efficiency. For instance, the heating steam in the first evaporation effect is typically live steam with higher temperature and pressure. After releasing latent heat in the heating chamber, it condenses into condensate for discharge. The flash steam generated serves as the heating source for the next evaporation effect. Since the flash steam has relatively lower temperature and pressure, it requires proper design and control to ensure effective heating of the solution in the next evaporation effect. Throughout this process, the evaporator of each evaporation effect fully utilizes the thermal energy from the flash steam generated by the previous evaporation effect, thus achieving multiple use of steam and significantly reducing steam consumption (as shown in Figure 2).

The unique structural design of the seven-effect evaporator is further demonstrated through its separate layout of the heating chamber and separation chamber. This configuration not only reduces equipment footprint but also minimizes heat loss. Separating those two chambers help avoid the uneven heat transfer that occurs in conventional integrated evaporators as a result of structural compactness and allows for heat transfer from the heating chamber to the solution in a more concentrated manner, thus significantly enhancing heating efficiency. The split design also offers distinct advantages in maintenance and servicing, facilitating staff to inspect, clean, and replace components, and thus reducing equipment maintenance costs and boosting equipment stability and reliability.

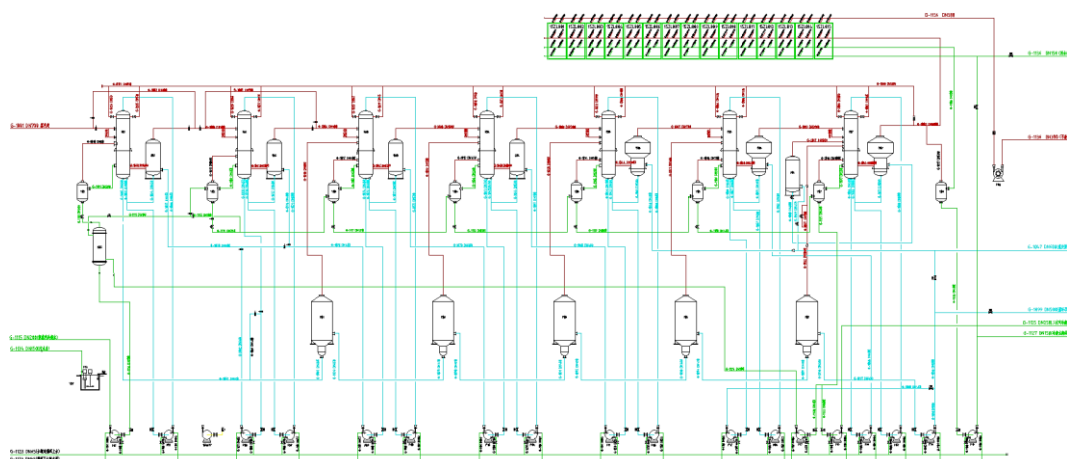


Figure 2. Process flow diagram of seven-effect two-stage full counter-current evaporation.

The seven-effect evaporator incorporates multiple patented technologies that enable its high-efficiency and energy-saving performance. The innovative designs of the film distributor and demister are particularly outstanding. As a critical component of the seven-effect evaporator, the film distributor ensures uniform distribution of sodium aluminate solution on the surfaces of the heating tube bundles, forming a consistent liquid film. Conventional film distributors have certain deficiencies in terms of the uniformity and stability of film distribution and are easy to result in uneven thickness of liquid film, thus affecting the evaporation efficiency. Jiu Ye Chemical Equipment Co., Ltd. has developed a new film distributor featuring a dual-layer structure composed of an upper film distributor plate and a lower film distributor plate (as shown in Figure 3).

Optimized shape, size, and distribution of film distribution holes and precise positioning of sieve holes enable the solution to be more evenly distributed on the surfaces of the heating tube bundles under gravity and centrifugal forces, forming a stable and uniformly thick liquid film. This structural design ensures complete film distribution of the feed solution, achieving more uniform film distribution with reduced clogging risks, thereby enhancing heat transfer efficiency and accelerating evaporation. Compared to conventional film distributors, this innovation boosts production capacity by approximately 10 % while extending the acid cleaning cycle. As an example, in practical applications, the new film distribution system allows the thickness deviation of the liquid film to be controlled in a very small range, ensuring thorough heating and evaporation of the solution on each heating tube bundle, significantly improving the overall performance of the evaporator.

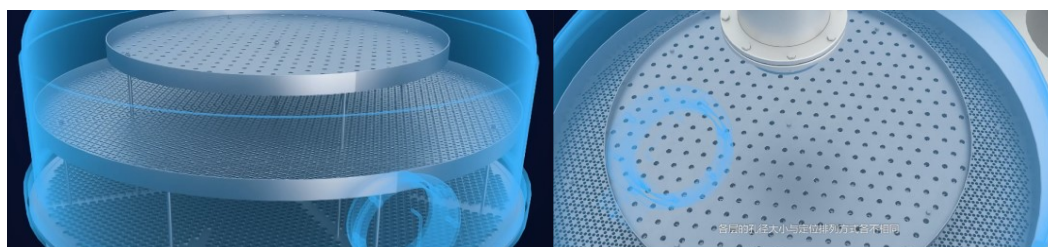


Figure 3. Schematic diagram of new film distributor.

The demister is designed to remove liquid droplets entrained in flash steam generated during evaporation, preventing these droplets from entering downstream evaporators and compromising both efficiency and product quality. Conventional demisters have low efficiency and cannot meet

the stringent requirements of seven-effect evaporators. Jiuye Chemical's innovative cyclone demister uses a novel design that utilizes centrifugal force to separate mist from the alkaline-containing steam. Unlike conventional louver-type baffled demisters, this design remains structurally stable, requires no flushing maintenance, delivers superior separation performance, and shares the same service life as the equipment (as shown in Figure 4). The new design enables efficient removal of liquid droplets from flash steam, significantly enhancing demisting efficiency and ensuring steam purity, thereby creating optimal conditions for subsequent evaporation processes.



Figure 4. Conventional louver demister (left) and new cyclone demister (right).

The industrial application of the seven-effect segmented new evaporator technology demonstrates that through heat balance optimization, intelligent control, and material innovation, production costs per tonne of alumina have been reduced by approximately 50 RMB (7 USD/t approx.). Based on last year's domestic output of approximately 80 million tonnes, this has resulted in a 24 million tonne reduction in steam consumption, up to 40 billion RMB (5.59 GUSD approx.) decrease in production costs, and up to 6.31 Mt reduction in carbon emissions. This technological paradigm provides a model for the global aluminium industry's low-carbon transition [5].

3. First Successful Application of Evaporative Condensers in Evaporator Station of an Alumina Refinery

Our company's independently developed evaporative condenser (Patent No. ZL201821142093.1) has been first applied in the evaporator station of an alumina refinery, offering new hope for the alumina industry to address high energy consumption and emissions [2]. By integrating the conventional last-effect flash steam condensation and circulating water cooling processes into a single system, the evaporative condenser not only significantly reduces equipment quantity and floor space requirements but also decreases both circulating water volume and electricity consumption. This innovative equipment combination provides a novel solution for energy conservation, emission reduction, and carbon mitigation in alumina production processes [6].

The application and economic benefit analysis of the evaporative condenser are introduced below with Chinalco Guangxi Huasheng Alumina Refinery Phase II project as an example.

3.1 Project Profile

Located in Fangchenggang City of Guangxi Zhuang Autonomous Region, Guangxi Huasheng Alumina Refinery has a total capacity of 4 Mt/y of alumina, comprising Phase I (2 Mt/y) and Phase II (2 Mt/y).

Phase I had 2 sets of 400 t/h evaporator units, using atmospheric condensers for the last-effect flash steam. Phase II had 2 sets of 500 t/h evaporator units, using evaporative condensers for the last-effect flash steam. The application of evaporative condensers in Phase II resulted in annual cost savings of 11.221 million RMB (1.57 MUSD/y approx.) and a cost reduction of 4.68 RMB per tonne of alumina produced (0.654 USD/t Al₂O₃ approx.).

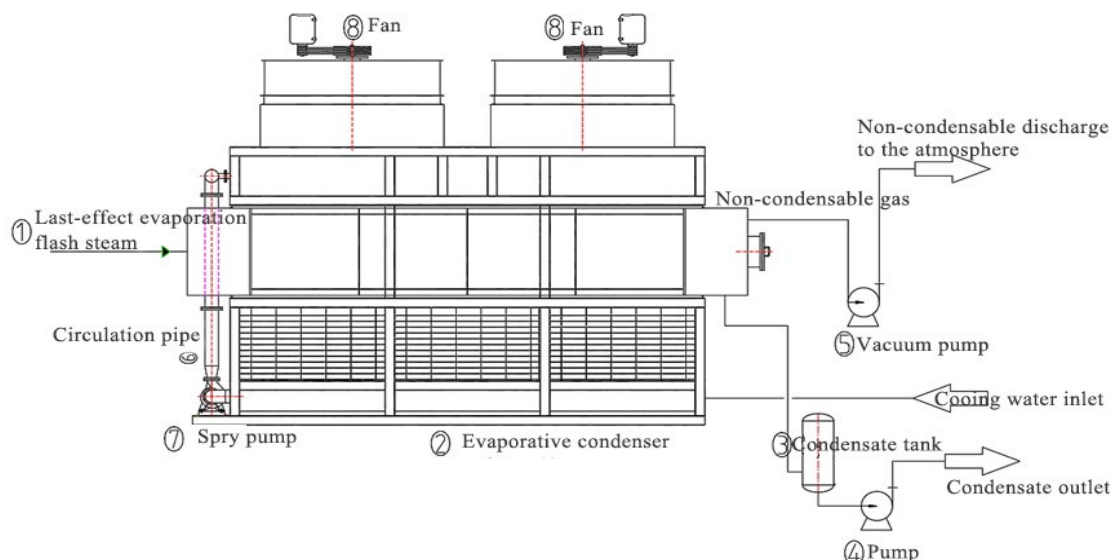


Figure 5. Flow diagram of evaporative condenser.

As shown in Figure 5: The last-effect flash steam (1) enters the tubes of the evaporative condenser (2). The water spray at the top contacts the tubes and some of the water spray vaporizes under the action of fast moving air, absorbing heat from the steam within the tubes, with the steam that loses heat turning into water, which flows into the condensate tank (3) and is then discharged by the condensate pump (4). Meanwhile, the water spray that absorbs heat turns into steam, which is extracted by the fan (8). The non-condensable gases are pumped out by the vacuum pump (5). The unvaporized water spray flows into the lower water tank, where it is pumped out by the spray pump (7) and recirculated through the spray pipe via the circulation pipe (6).

3.2 Working Principles of Evaporative Condenser

As an energy-efficient heat exchange device, the evaporative condenser operates by absorbing latent heat during water evaporation to conduct heat. Owing to its high thermal efficiency, energy-saving performance, compact design, and easy installation, it found its first application in the chemical and power industries. After improvements by our company, this technology was first applied in the alumina industry starting from 2016. The evaporative condenser uses a combined heat exchange method of "evaporative cooling + air convection" to achieve steam condensation [7].

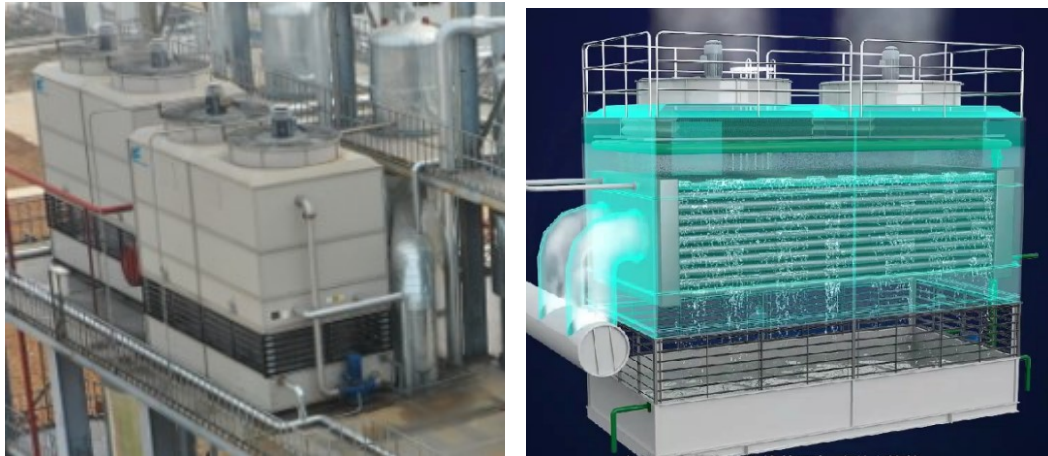


Figure 6. Photo (left) and 3D simulation picture (right) of evaporative condenser.

It works by the following principles. The core of the evaporative condenser is to use the dual action of latent heat of water evaporation and air convection heat exchange to rapidly condense steam. Its operation process can be divided into four coordinated stages: steam condensation, water circulating evaporation, air forced heat exchange and non-condensable gas treatment [8] (as shown in Figure 7).

1. Steam introduction and initial condensation

The last-effect flash steam generated by the evaporator station (typically at high temperatures and containing trace amounts of alkaline or corrosive components) enters the steam distribution chamber on the side of the condenser side through pipelines. Inside the tube side, the steam first contacts the cooling water (shell-side circulating water) evenly distributed by the spray system. After getting into indirect contact with the low-temperature water, some of the steam releases latent heat and undergoes initial condensation, forming liquid water.

2. Evaporative cooling and air forced heat exchange

After steam condensation, water film or fine water droplets are formed and ambient air is forcibly introduced by the induced draft fan at the top. When air passes through the bottom water tank in counter-current or cross-flow mode, heat and mass transfer is carried out with water and steam.

3. Water circulation and heat discharge

The condensed water mixes with water spray and flows into the bottom collection tank. Some of the water is recirculated to the top spray system via the circulation pump, maintaining the continuity of the water film coverage and evaporative cooling. The remaining water (lost to evaporation and drainage) requires replenishment with fresh water. Through water treatment systems (including filtration and chemical dosing), the water quality is controlled to prevent scaling or corrosion issues common in alumina production. The hot and humid air after heat absorption is then exhausted into the atmosphere by the fan, completing the final heat release.

4. Vacuum maintenance and non-condensable gas treatment

The sudden volume reduction of steam after condensation (vacuum effect) and the suction from the fan work together to maintain a low-pressure environment in the system, promoting continuous steam discharge within the evaporator. The non-condensable gases (such as air and CO₂, etc.) mixed in the steam are discharged by the vacuum pump or jet suction device to prevent accumulation that could affect condensation efficiency.

3.3 Structure of Evaporative Condenser

The structure of the evaporative condenser is shown in Figure 7.

The last-effect flash steam from the evaporator station enters the flash steam collection chamber ① within the heat exchange unit through the steam inlet. The flash steam is evenly distributed the flash steam collection chamber ① into the heat exchange element ②, where it undergoes heat exchange and condensation. The condensate flows out from the heat exchange element ② and collects in the condensate collection chamber ③ within the heat exchange unit. Next, the condensate in the condensate collection chamber ③ enters the condensate tank ④ and is recovered by the condensate pump ⑤. Meanwhile, the non-condensable gases are collected in the non-condensable gas collection chamber ⑥ within the heat exchange unit and discharged by the vacuum pump ⑦.

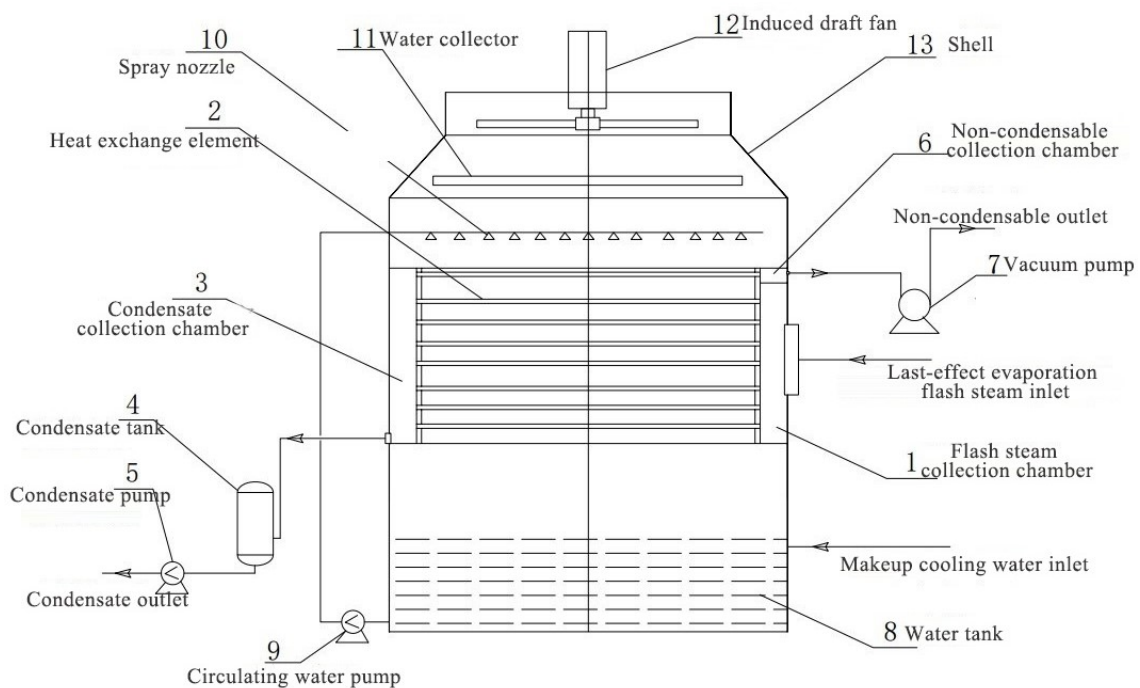


Figure 7. Schematic diagram of structure of evaporative condenser system.

The heat released from the condensation of flash steam in the heat exchange element ② causes the spray water outside the heat exchange element to evaporate. Air is introduced into the lower section of the heat exchange element ② by the induced draft fan ⑫ and exhausted to the atmosphere from the upper section. The absorption of a large amount of latent heat during spray water evaporation and the absorption of sensible heat during water temperature rising take away the heat in the heat exchange element ② and cause the steam in the heat exchange element ② to condense. At the same time, taking away of the heat by the cold air flow entering from the bottom of the heat exchange element ② cause the water that has not evaporated to cool and flow into the lower water tank ⑧. Next, the water is sent to the top of the heat exchange element ② by the circulation pump ⑨. Then, after being sprayed by the spray nozzle ⑩, it forms a water film layer along the surface of the heat exchange element ② within the heat exchange unit to realize the recycling of the spray water.

3.4 Equipment Configuration

To achieve good energy performance, each of Guangxi Huasheng's 2 sets of 500 t/h evaporator units is equipped with 20 evaporative condensers arranged in a back-to-back configuration, where the core equipment (e.g., evaporators, heaters, and separators) of the 2 sets of evaporator units is symmetrically arranged in a back-to-back manner, creating shared operational or pipeline passageway between them. The two sets of units have parallel axes, and the equipment is oriented in opposite directions, forming a compact double-row structure (as shown in Figure 8).

Twenty evaporative condensers are installed on the top platform of the evaporator's simple steel structure, arranged in a modular array configuration (e.g., 10×2 matrix). The condensers are properly spaced to ensure adequate ventilation and heat dissipation. This layout not only achieves the condensation of the last-effect flash steam but also saves land occupation and reduces investments in cooling towers.

This layout offers four advantages as follows:

1. Enhanced natural ventilation: The elevated platform height facilitates air circulation, utilizing ambient wind to accelerate the evaporation of condenser spray water and improve cooling efficiency.
2. Gravity drainage convenience: Condensate flows naturally to the lower-level collection system through gravity, reducing energy consumption.
3. Floor space optimization: Eliminates floor space occupied by the condensers, freeing up space for other equipment or operations.
4. Noise and steam isolation: The elevated layout reduces the impact of the operational noise of the condensers and steam on people on the ground.

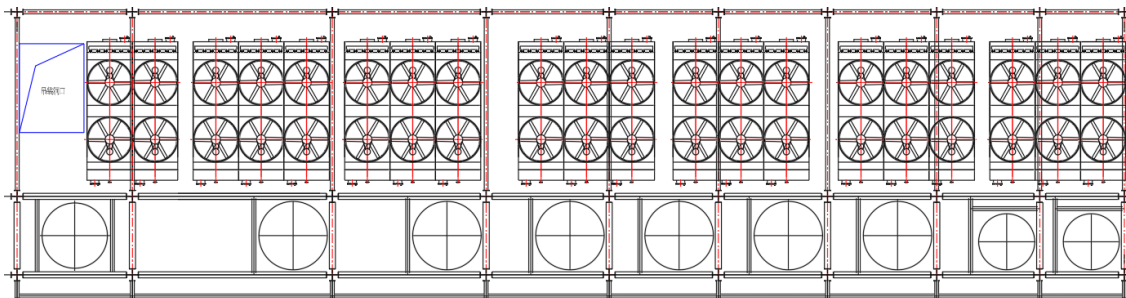


Figure 8. Layout plan of 20 evaporative condensers.

3.5 Energy-saving and Consumption Reduction Performance

The operational data comparison between the direct water-cooled condenser system for the last-effect flash steam from Phase I (500 t/h) and the evaporative condenser system for Phase II (500 t/h) at Guangxi Huasheng's evaporator stations is presented in Table 1. The table reveals that the evaporative condenser system in Phase II achieves approximately 43 % water conservation compared to the conventional atmospheric condenser system used in Phase I. A comparative analysis of economic performance between these two solutions, including their one-time investments and operational costs, is detailed in Table 1.

Table 1. Economic analysis comparison of two condensation options.

Item	Atmospheric Condenser			Evaporative Condenser		
	Qty.	Total cost (kRMB)	Power kW	Qty.	Total cost (kRMB)	Power kW
1. One-time investment						
Condenser	1	513.5		20	15 106.5	1030
Cooling tower	2	4 808.8	560			
Pump	3	1 859.2	1600			
Tank	1	5 802.5				
Process pipe and valve	1 batch	2 353.5		1 batch	1 012.5	
Electrical instrument automation	1 batch	2 855.5		1 batch	1 033.5	
Sub-total		18 193			17 152.5	
2. Operational cost (per year)						
Circulating water consumption (m ³ /h)	6000			3400		
Electricity (kW)	1728			824		
Electricity expense	7 258.5			3 463.5		
3. Data summary (calculation based on 2 sets of evaporator units)						
One-time investment difference	2.081 MRMB (The atmospheric condenser costs more than the evaporative condenser.)					
Operational cost difference (electricity)	7.59 MRMB/y (The atmospheric condenser costs more than the evaporative condenser.)					
Other operational cost difference (water, with 3 RMB/m ³ price)	1.56 MRMB/y (The atmospheric condenser costs more than the evaporative condenser.)					
Cost reduction per tonne of alumina	4.68 RMB/t Al ₂ O ₃ (The evaporative condenser costs less than the atmospheric condenser.)					

From the comparison in the above table, it is evident that:

- 1) The investment of the evaporative condenser option is 2.081 million RMB less than that of the atmospheric condenser option.
- 2) The operational cost of the evaporative condenser option is 9.14 million RMB less than that of the atmospheric condenser option.
- 3) The cost alumina per tonne of alumina can be reduced by 4.68 RMB with the evaporative condenser option compared with the atmospheric condenser option.

The application of the evaporative condensers in alumina production offers such advantages as energy saving, water saving, reduced operational costs, etc. For the alumina industry that urgently needs cost reduction, there's a necessity to use this device into the flash steam condensation system of the evaporator units. The successful application of the evaporative condensers at

Guangxi Huasheng demonstrates their promising prospects in the alumina industry. This technology not only reduces land investment and operational expenses but also delivers significant economic and social benefits.

4. Analysis of Application of New Eight-effect Sectionalized Evaporators in Alumina Refinery

It is well known that the evaporation process is one of the most energy-intensive stages in alumina production. Since Jiuye Chemical developed the world's first seven-effect evaporator unit, both low-concentration (spent liquor concentration ≤ 215 g/L) and high-concentration (spent liquor concentration ≥ 240 g/L) alumina production can use the seven-effect evaporator unit. However, significant room for improvement exists in thermal efficiency and economic performance for low-concentration spent liquors (caustic soda concentration ≤ 215 g/L).

The eight-effect evaporator can significantly reduce steam consumption [3] in theory by increasing the number of effects, optimizing the distribution of temperature difference and heat balance calculation design. This report conducts an analysis from four aspects: technical feasibility, energy saving benefits, economic benefits and patent layout.

4.1 Technical Feasibility Analysis

1. Heat balance and temperature difference matching

For the characteristics of low-concentration spent liquor, the eight-effect evaporator achieves heat balance through optimized temperature difference distribution. The temperature difference of each effect is controlled to be 3–4 °C, with the effective temperature difference equivalent to that of the seven-effect evaporator (high-concentration operation condition), which can ensure stable system operation. Jiuye Chemical has successfully executed at least fourteen high-concentration seven-effect evaporators in China, all of which operate stably and reliably. In other words, the eight-effect evaporator is sure to operate stably also under low-concentration spent liquor operation conditions.

According to the heat balance calculation, the temperature difference of the eight-effect evaporator under low-concentration operation conditions is equivalent to that of the seven-effect evaporator under high-concentration working conditions, there is no risk of insufficient heat power, and the low-concentration eight-effect evaporator unit can fully run smoothly.

2. Key technological innovation and risk analysis

Accurate and scientific heat balance calculations and area allocation for each effect are the critical technologies in the low-concentration eight-effect evaporator unit. Jiuye Chemical has extensive experience in calculation and design. Operational data from the high-concentration seven-effect evaporator unit confirms zero operational risks for the low-concentration eight-effect evaporator unit. Should any issues arise during production, one effect can be isolated to let the unit operate as a seven-effect evaporator unit, with the isolated effect serving as a standby effect. And the isolated seven-effect evaporator unit has larger operational areas and enhanced reliability. This demonstrates that the technology carries low operational risks.

4.2 Energy-saving Benefit Analysis (Saving Steam)

The heat balance calculation results show that the steam to water ratio of the eight-effect evaporator unit can be reduced by approximately 0.03 compared with that of the seven-effect evaporator unit. Taking an alumina refinery with an annual capacity of 1 200 kt/y as an example, utilization of a 600 t/h evaporator can save approximately 150 000 tonnes of steam annually.

Based on the steam price of 180 RMB/t in China, the annual steam cost saving reaches up to 27 million RMB.

For regions where steam is expensive, such as Guinea, where the boiler operates on liquefied natural gas or heavy oil, the steam price could be above 300 RMB/t (42 USD/t approx.). With an annual capacity of 1 200 kt/y of alumina with 600 t/h eight-effect evaporators, the annual steam cost saving can reach up to 45 million RMB (6.3 MUSD/y approx.).

4.3 Economic Benefit Analysis

For the same 1.2 Mt/y capacity refinery, needing a 600 t/h evaporating capacity, the retrofitting with eight-effect unit requires an investment of approximately 25 million RMB more than the seven-effect evaporator unit (including equipment, steel structure, installation and instrument and electrical control system).

As seen previously, the utilization of the eight-effect evaporator unit brings an additional income (through energy savings) of 45 million RMB/y (based on a steam price of 300 RMB/t).

Investment payback period: less than seven months, excluding government energy saving subsidies.

4.4 Patent Layout and Intellectual Property Right Protection of New Eight-effect Evaporators

Regarding the new eight-effect evaporator developed by Henan Jiuye Chemical, the following details are provided regarding the patent applications:

1. Authorized patents:

"Eight-Effect Two-Stage Cross-flow Evaporator Unit for Concentrated Sodium Aluminate Solution" Patent No.: ZL 2013 2 0620522 2.

2. Accepted patents (Three):

1) "Eight-Effect Multi-Stage Sodium Aluminate Solution Evaporator Unit" Invention Patent Application No.: 202510473827.2

2) "Eight-Effect Two-Stage Sodium Aluminate Solution Evaporator Unit" Utility Model Patent Application No.: 202520714213.4

3) "Eight-Effect Three-Stage Sodium Aluminate Solution Evaporator Unit" Utility Model Patent Application No.: 202520714415.9

4.5 Conclusions

The new eight-effect evaporator has significant advantages in low-concentration alumina spent liquor evaporation:

Technically feasible: The heat balance calculations show that the temperature difference matches the seven-effect high-concentration evaporator, posing no operational risks.

Economic efficiency: An annual steam cost saving of approximately 30 million RMB (based on a steam price of 180 RMB/t) is achieved, with an investment payback period of slightly less than a year. For a steam price of 300 RMB/t, the payback period is less than seven months.

Protection by patents: Core technologies have been authorized, with reduced intellectual property right risks.

5. Exploration of New Technologies for Future Evaporators

5.1 Possibility of Application of MVR Evaporators in Alumina Industry

In the past, due to their limited compression ratios and capacities, steam compressors could not be used as the evaporators of the alumina industry where the boiling point rises significantly and the single-unit evaporation water volume is also large. Now, with an enhanced compression ratio, it is possible to achieve heat exchange in the alumina industry even when the boiling point rises by less than 15 °C. With the compression capacity reaching 200 t/h, the alumina industry's baseline water evaporation requirements are also met. Small evaporators for multiple varieties of alumina can be fully realized.

Taking Luoyang Zhongchao New Materials Co., Ltd. as an example, the plant currently relies on external steam supply at a relatively high cost exceeding 220 RMB/t (31 USD/t approx.), with insufficient supply – particularly unstable supply during winter months. The plant leadership organized multiple technical exchanges with our company and decided to retrofit two existing six-effect 40 t/h evaporator units into seven-effect or MVR evaporators. A comparison done by our company between the two solutions of seven-effect evaporator unit and MVR evaporator unit showed clearly that the MVR evaporator significantly reduced operational costs:

The 40 t/h seven-effect evaporator unit consumes 7.5 t/h of steam and 690.5 kW of electricity, with an operational cost of $7.5 \times 200 + 690.5 \times 0.8 \times 0.7 = 1\,886.7$ RMB/h;

The 40 t/h MVR evaporator unit consumes 1.2 t/h of steam and 2 302 kW of electricity, with an operational cost of $1.2 \times 200 + 2\,302 \times 0.8 \times 0.7 = 1\,529.1$ RMB/h.

The annual cost saving from the MVR evaporator unit over the seven-effect evaporator unit is $1\,886.7 - 1\,529.1 = 357.6$ RMB/h, saving approximately 3 million RMB/y (per unit) of operational cost annually.

5.2 Working Principles and Technical Difficulties of MVR Evaporators

The MVR falling-film evaporator is an efficient evaporation device that integrates mechanical vapor recompression (MVR) technology with falling-film evaporation. Widely used in such industries as hydrometallurgy, chemical processing, food production, pharmaceutical manufacturing, and environmental wastewater treatment, this device features a compressor that heats and pressurizes flash steam for reuse as a heat source. This design significantly reduces energy consumption while achieving efficient heat transfer and minimizing scaling risks through the means of falling-film evaporation.

5.2.1 Working Principles

Evaporation process:

The liquid material enters the falling-film evaporator from the top, where it is evenly distributed through a distributor onto the inner walls of heating tubes, forming a thin film flow. The heating medium (e.g. steam) heats the tube from the outside, rapidly evaporating the liquid film. The resulting flash steam and concentrate are discharged from the bottom.

Steam recompression:

The flash steam enters a mechanical compressor, where it is heated and pressurized before returning to the evaporator as a heat source, achieving thermal energy recycling.

Key parameters:

Compression ratio: typically 1.2–2.0; temperature rise: 10–20 °C.

Condensation and discharge:

The flash steam condenses within the heating tubes, releasing latent heat to heat the solution, with the condensate discharged from the system.

5.2.2 Technological Advantages

High-efficiency and energy-saving:

Remarkable energy-saving performance enables extensive application of renewable energy sources like wind and solar power.

Low-temperature evaporation:

Operating at low temperatures, it is suitable for heat-sensitive materials.

Small footprint:

The compact structure eliminates the need for boilers and cooling towers, saving space.

Highly automated:

Fully automated operation reduces manual intervention.

Eco-friendly and low-carbon:

Reduce steam consumption and cooling water usage, lowering carbon emissions.

5.2.3 Technical Difficulties and Solutions

Compressor selection and maintenance:

Technical difficulties:

As the core component of the MVR system, improper compressor selection or inadequate maintenance can lead to reduced efficiency or even equipment failure.

Solutions:

Select appropriate compressor types based on evaporation capacity and temperature rise requirements.

Perform regular maintenance (e.g., impeller cleaning, lubricant replacement).

High boiling point elevation with small material temperature difference:

Technical difficulties:

Single-effect single-body exhibit small temperature differences, large areas, and high investment.

Solutions:

Optimize design through meticulous calculations to convert single-effect single-body into single-effect multi-body configuration.

Scale build-up and blockage:

Technical difficulties:

Scaling on heating tube walls of high-concentration materials reduces heat transfer efficiency.

Solutions:

Implement periodic chemical cleaning (acid or caustic cleaning);

Add scale inhibitors (e.g., polyacrylic acid);

Use scraper-type falling-film evaporators.

5.3 Exploration of Using MVR Evaporator in Sodium Aluminate Solution Concentration

Based on the characteristics of the sodium aluminate solution in alumina refineries, we developed a single-effect multi-body multi-unit MVR evaporator that addresses the difficulties of small temperature differences and large areas, thus overcoming the technical difficulty that MVR evaporators could not be applied in the alumina refinery evaporator stations in the past.

Existing challenges and solutions:

1. Heat transfer efficiency reduction caused by scaling

Solutions: Implement tubular forced circulation + online monitoring, combined with periodic cleaning (acid cleaning every 1–2 months).

2. High boiling point elevation requirements for compressors

Solutions: Select multi-stage centrifugal or screw compressors to enhance temperature rise capacity (ΔT up to 20–25 °C).

3. Impact of solution fluctuations on system stability

Solutions: Install buffer tanks and automatic concentration regulation systems to reduce feed fluctuations.

6. Common Problems of and Solutions for Evaporators in Alumina Refineries

6.1 Alkaline Embrittlement and Corrosion of I-effect and II-effect Heat Exchange Tubes

Existing problems: alkaline brittleness refers to the brittle cracking occurring in metallic materials due to the combined effects of tensile stress and exposure to high-concentration alkaline medium. In terms of bauxite ore composition, most of the Chinese bauxite ores are diasporic, which requires high-temperature and high-pressure digestion for processing. Additionally, the caustic soda concentration (Na_2O_k) is typically greater than 240 g/L. For such materials, high-concentration evaporators are designed. In contrast, processing of the gibbsitic bauxite ores from the rest of the world requires a lower caustic soda concentration (Na_2O_k) of typically < 200 g/L, for which low-concentration evaporators are designed.

The main causes of alkaline brittleness in sodium aluminate solution evaporator include: 1. Highly alkaline environment; 2. Welding residual stress and working stress; and 3. Improper material selection.

High-concentration evaporators are highly prone to experience pipe wall corrosion and alkaline embrittlement in their heat exchange and process pipelines, which is a widespread issue. Our solution involves supervising the whole steel pipe manufacturing process, including tube blank sourcing, heat treatment (normalizing and annealing), non-destructive testing, etc. Implementing rigorous workmanship measures ensures the selection of premium steel pipes effectively resolve this problem.

In high-concentration evaporators, cracking in the first-effect section is particularly prevalent. This occurs due to the spent liquor's caustic soda concentration (Na_2O_k) exceeding 240 g/L. With prolonged exposure to high-concentration caustic soda (Na_2O_k) solutions and due to the combined effects of environment and stress, alkaline embrittlement is particularly likely to happen. Typical manifestations include transcrystalline crack formation in equipment welds, flanges, or stress concentration zones, ultimately leading to brittle fracture or leakage. For instance, at Guangxi

Xinfa, they replaced heat exchange tubes in the first-effect heating chamber with stainless steel tubes, and even changed process pipelines from I to III effects into stainless steel pipes, and they also installed composite plates of stainless steel and carbon steel for the lower section of the separation chamber. All of those measures clearly demonstrate that cracking of high-concentration evaporator is a widespread issue.

Solutions: since Xinfa Group used our company's China's first 240 t/h seven-effect high-concentration evaporators in 2013, we have been focused on and studied how to address the critical issue of high-concentration evaporator cracking, a persistent challenge in the industry. Similar problems also occurred in the equipment from other Chinese manufacturers in the same industry and remained unsolved for years. We conducted extensive research and field trials and learned valuable lessons the hard way. Finally, we achieved a breakthrough by synergizing material selection with heat treatment processes, effectively resolving this critical problem. For high-concentration evaporators, particularly the heating chambers of first-effect evaporator, proper heat treatment methods are essential. Critical parameters include annealing temperature and holding time and normalizing temperature and holding time. Those measures can eliminate over 97 % of stress, ensuring the evaporator remains crack-free for years.

6.2 Widespread Insufficient Water Evaporation in Summer

It is well known that heat balance calculation is the core and soul of evaporator design. Without scientific heat balance calculation, the data provided by the last-effect water evaporation is incorrect, resulting in the wrong configuration of evaporator circulating water volume, so that the water evaporation and steam-to-water ratio in summer are not up to standard, resulting in a significant reduction in production capacity.

Case 1: An alumina refinery in Hebei Province initially used a 500 t/h evaporator unit. The data from an equipment manufacturer indicated that the last-effect flash steam was 80 tonnes, and the recommended circulating water volume was 3 600 tonnes only. The refinery configured its system accordingly. However, during summer operations, equipment malfunction occurred with a sharp decline in vacuum level, drastic reduction in water evaporation, and increased steam-to-water ratio. Heat balance calculations showed the actual last-effect flash steam should have been 110 tonnes, requiring approximately 6 000 tonnes of circulating water.

Case 2: Similar issues also occurred at an alumina refinery in Chongqing. The refinery's seven-effect evaporator unit with super concentrator failed to meet design capacity and suffered alkali leakage in the last effect. The primary cause was flawed design by the equipment manufacturer, whose heat balance calculations were inaccurate. The equipment manufacturer provided the refinery with a design data that specified 80 t/h of last-effect water evaporation, while the actual maximum last-effect water evaporation could reach 140 t/h. The evaporator manufacturer designed the last-effect separation chamber and circulating cooling system based on 80 t/h. This resulted in significantly smaller separation chamber diameters than required, causing alkali leakage due to high steam velocity in empty towers. As a result, the circulating cooling water was configured much less than required, leading to high circulating cooling water outlet temperature and the failure to meet the design vacuum level requirements. The reduced effective temperature difference of the evaporator unit resulted in the evaporator unit failing to achieve the designed capacity and lead to high steam-to-water ratio.

Case 3: On March 3, 2025, Chinalco Shanxi Alumina Refinery tasked our company with retrofitting their seven-effect evaporators. According to investigation, the refinery's tender specifications required a 370-tonne capacity evaporator unit. However, the equipment manufacturer did not know how to design seven-effect evaporator units and they did the design by the simple addition of an extra effect to their existing six-effect evaporator units. The resulting

seven-effect unit design by the equipment manufacturer only achieved 220 tonnes of water evaporation, merely 60 % of the required capacity in the tendering document, with both water evaporation and steam-to-water ratio never up to standards.

6.3 Widespread Alkali Leakage of Last-effect Evaporators in Large Evaporator Units

The alkaline leakage in the last effect primarily stems from flawed evaporator unit design. For instance, the design data specifies 80 t/h water evaporation for the last effect, but the actual maximum last-effect water evaporation reaches 140 t/h, and the evaporator manufacturer configures the separation chamber and circulating cooling water system based on the 80 t/h water evaporation. This results in the separation chamber diameter being significantly smaller than required, causing alkaline leakage in the last effect due to high steam velocity in the empty towers. Additionally, the circulating cooling water system is configured much less than required, leading to high circulating cooling water outlet temperature and the failure to meet the design vacuum level requirements. The reduced effective temperature difference of the evaporator unit results in the evaporator unit failing to achieve the designed capacity and leads to high steam-to-water ratio. Solutions: Stabilize the vacuum degree of last effect at -0.088 MPa, control the temperature of the last-effect solution at 65–75 °C, configure appropriate circulating water volume according to the evaporation capacity of the last effect, avoid overload operation, and design an appropriate volume for the last-effect separation chamber according to heat balance calculation.

7. Conclusions

- 1) The application of the innovative seven-effect evaporator technologies has reduced the steam-to-water ratio of the original evaporator station from 0.3 to below 0.17, lowering the production cost per tonne of alumina by approximately 50 RMB. Based on China's alumina output of approximately 80 million tonnes in the last year, it results in a decrease of up to 24 million tonnes in steam consumption, a production cost reduction of up to 40 billion RMB, and a carbon emission reduction of up to 6.31 Mt.
- 2) The innovative application of evaporative condensers in alumina evaporator stations has brought approximately 3 kWh of electricity savings per tonne of water evaporated. With each tonne of alumina production requiring 3 tonnes of water evaporation, it enables China's alumina industry to save up to 720 GWh of electricity annually, resulting in an electricity cost saving of up to 500 million RMB and a direct carbon reduction of up to 484 kt.
- 3) 6.794 million tonnes of CO₂ is equivalent to the annual carbon sequestration of approximately 1.85 million hectares of forest (based on 3.67 tonnes sequestered per hectare of forest per year) or the reduced annual emissions from 2.83 million fuel-powered vehicles (based on 2.4 tonnes emitted per vehicle per year). It has made a great contribution to the evaporator technologies in the alumina industry.

Henan Jiuye Chemical Equipment Co., Ltd.'s new evaporator technologies prove that: "Low carbon is not a cost, but competitiveness; innovation is not an option, but the law of survival." We are willing to join hands with partners in the industry and use the pen of technological innovation to write a green chapter for the high-quality development of the alumina industry.

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